A gasfet preamplifier for 432MHz with 0·5dB noise figure

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Introduction

This article describes the construction of a state-of-the-art preamplifier for 432MHz with a noise figure of around 0·5dB (a noise temperature of 35K), using a gallium arsenide fet (gasfet). It also outlines the importance of the other components of the receiving system, such as feeder losses and the subsequent stages of the receiver which can also affect the noise figure of the overall system. Also included is a design for a second-stage preamplifier using a BFR34A which has a noise figure of around 2dB. These preamplifiers are in current use by the authors in their 432MHz moonbounce system. The main emphasis is on achieving very low noise figures, but the devices are also capable of very good strong signal performance if a slightly poorer noise figure is acceptable—this trade-off would probably be made if the preamp was to be used only for normal terrestrial purposes.

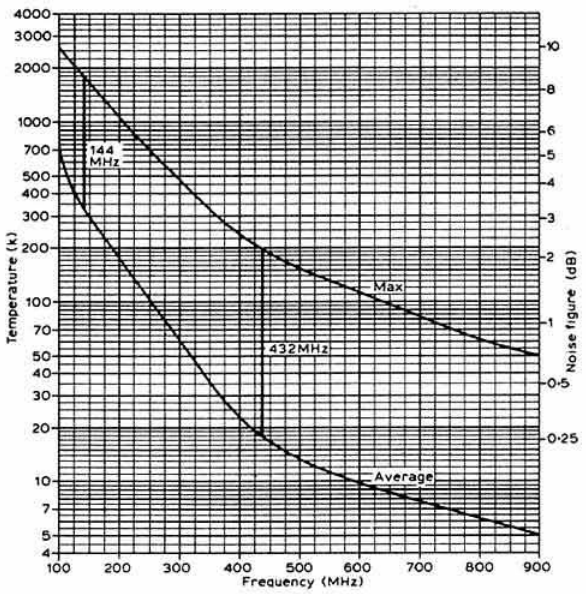

Fig 1. Plot of sky temperature against frequency. *(Errata*: **In Figs 1, 2, 3, 9 and 10, "k" should read "K", signifying °Kelvin)**

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The benefits obtained from a low receiver noise figure will depend on the ambient noise level, which is the sum of contributions from several sources. Thermal noise will be picked up by the antenna from both the sky and the earth—man-made noise sources will be ignored, as they are not a fundamental limitation, and are usually only of short duration.

Typical values of the noise level from the sky are given in Fig 1; at some time during the day the most noisy parts of the sky can be near the horizon, and so may be in the antenna beam. The sky's noise level is expressed both as a noise figure in decibels and as an absolute temperature; this is the value of system noise figure or temperature for which the noise from the sky will be equal to the noise generated in the receiving system. The noise contribution from the earth will be at a temperature of around 290K (3dB nf), although this decreases at lower frequencies where the ground reflects, rather than absorbs, the signals. Feeder losses also introduce noise as well as attenuating the wanted signal. Finally there is the noise generated in the receiver front-end. So it can be seen that the noise from the receiver preamplifier is only a part of the noise present at the receiver output.

On the lower vhf bands the thermal noise from the sky does not make it worthwhile to use a receiver with a noise figure of less than about 2dB. Even if an ideal, noiseless receiver were used, the s:n would only be improved by a decibel or so. At higher frequencies, however, particularly when the antenna is beaming upwards, less noise is picked up from the ground and the noise level from the sky is also much lower, so it is worthwhile building receivers with a much lower noise figure. On

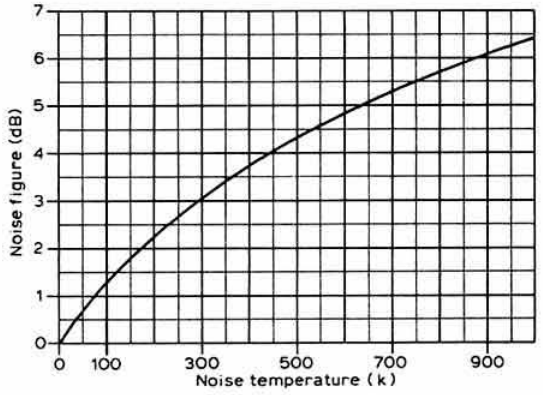


Fig 2. Graph for converting noise figure to noise temperature

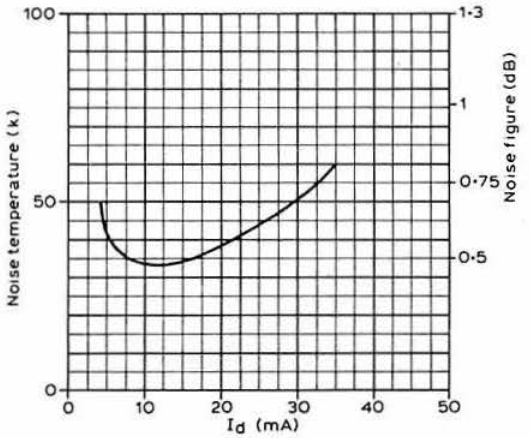


Fig 3. Variation of noise temperature of the gasfet preamp with drain current

432MHz, with the antenna pointing skywards for satellite or moonbounce work, the improvement in s:n obtained by going from a 3dB to a 0·5dB nf could be up to 6dB, so the effort involved in developing very low noise figure preamps is well rewarded.

This improvement, much greater than the difference between the two noise figures, may seem illogical, but it is a consequence of noise figures being expressed relative to room temperature (290K), so they cannot be used directly to calculate the s:n when the noise source is at a different temperature. The concept of noise temperature is a better way of expressing both receiver and external noise levels, and is very useful in these cases. It is a means of specifying noise powers, eg the equivalent noise power at the input of the amplifier, and the actual noise power from the sky.

The available noise power P, is directly proportional to absolute temperature T, $P = k \times T \times B$, where k is Boltzman's constant, $1{\cdot}38 \times 10^{-23}$ J/K, and B the bandwidth (Hz), so it is very simple to calculate s:n ratios using temperatures to represent the noise powers. The relation between noise figure and noise temperature is shown in Fig 2, which is a plot of the following relation:

$$NF_{dB} = 10 \log \left(1 + \frac{T}{290}\right)$$

Noise figures of 2-3dB are readily obtainable on 432MHz using inexpensive bipolar devices. The lower limit is about 1dB, but this figure is not easily achieved.

Previously, the way to improve on these noise figures was to use rather exotic techniques such as masers and parametric amplifiers, but gasfets have recently become available and they offer a very simple solution to the problem. They are really intended for use in the 2-20GHz region where they can give noise figures of 1-3dB with associated gains of 15-8dB. These figures are themselves quite impressive, but their performance is even better at lower frequencies (uhf). The devices themselves have noise figures of around 0·3dB (21K) in the 300-600MHz region, with gains of 18dB achievable with an untuned output circuit. The noise figure begins to rise again below 300MHz due to flicker noise. Their strong signal performance is superior to bipolar devices because they produce the best noise figure at a higher device current, typically 10-15mA, whereas bipolars optimize at around 4mA. They will also hold a very low noise figure up to much higher drain currents, 20-30mA, see Fig 3. For many terrestrial applications, this high dynamic range will be more important, so the device would be run at 30-40mA drain current, giving an nf of around 1dB.

The one major problem in their use is that they have a very high input impedance. Bipolars have input impedances which are relatively close to 50Ω, typically a few hundred ohms, so they are quite easy to match in either narrow or broadband systems, leaving open the option of fitting a narrow, low-loss, bandpass filter in front of the preamp. On the other hand, gasfet input impedances are many tens of kilohms, so a very high Q network is necessary to step up the impedance with low loss, and it is consequently difficult to make them operate over a broad bandwidth. This is a disadvantage for many professional applications, but actually a positive benefit for amateur applications, as it requires the construction of a very narrow bandwidth low-loss input matching circuit which will reject out-of-band signals and reduce the number of spurious products generated in the receiver. This is particularly effective, since the filter is in front of all the active devices in the receiver. Broadband preamps can suffer badly in this respect from the large number of strong signals present in the vhf/uhf bands. This preamp has been used in close proximity to a 400W station on 144MHz, with both antennas on the same mast, 6ft apart, and no problems were experienced.

Noise matching

The best possible noise figure will not be obtained from a device just by stepping up the 50Ω input to a value equal to the complex conjugate of the device's input impedance, which is the condition for maximum power gain, and therefore also results in the preamp presenting a matched load to the input line. For the best noise figure the device must be fed from a specific impedance which is usually quite different to its input impedance, and so the preamp will mismatch the input line. For bipolar devices this mismatch corresponds to a vswr of around 2:1 at vhf.

Gasfets, however, need a much larger mismatch, in the region of 15:1. A consequence of this large mismatch is that the input matching required for maximum gain and minimum noise figure will be very different. Typical values of the impedances required for these two conditions were measured, and are shown in Fig 4 for several devices, a GAT5, a GAT4 and an ALF1000.

These values can also be expressed in terms of S parameters but, since the impedances involved are so much greater than

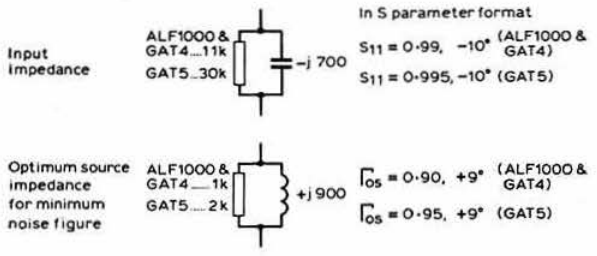

In S parameter format
Input impedance
ALF1000 & GAT4 ... 11k
GAT5 ... 30k
-j 700
S11 = 0·99, -10° (ALF1000 & GAT4)
S11 = 0·995, -10° (GAT5)
Optimum source impedance for minimum noise figure
ALF1000 & GAT4 ... 1k
GAT5 ... 2k
+j 900
Γos = 0·90, +9° (ALF1000 & GAT4)
Γos = 0·95, +9° (GAT5)

Fig 4. Input and optimum source impedances for several gasfets

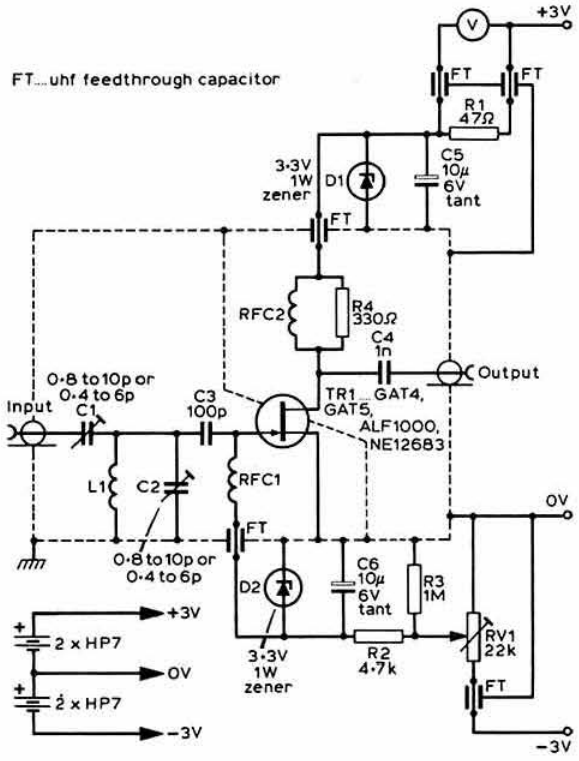


Fig 5. Circuit of the gasfet preamplifier

50Ω, it is not a very useful way of expressing them. The function of the input matching network is therefore to transform the 50Ω input to approximately 2kΩ in parallel with an inductive reactance of 900Ω. This reactance roughly cancels out the input capacitance of the fet.

The input resistance of the fet is very much larger than this value, so it has little effect on the loaded Q of the input circuit. The loaded Q required is about 15–30, depending on the type of fet. The most important feature of this preamp design is the input matching circuit, which has a very high unloaded Q (approximately 1,000) in order to reduce the losses in it, which will degrade the noise figure.

Construction

The circuit of the gasfet preamplifier is given in Fig 5. It is built on double-sided pcb which is used as a ground plane, and the whole amplifier fits in a 4·4 by 2·4 by 1·25in diecast box, with the ground plane replacing the lid. The screens are also made from double-sided pcb for rigidity and ease of soldering, and the covers for the input inductor L1 are made from thin brass or copper foil. The layout is shown in Fig 6 and the photograph.

First, mark and cut out the pcb to fit over the top of the box, and drill holes for the mounting screws in each corner. Mark the position of the posts in the corners of the box on the pcb, so as to avoid mounting anything on the board which will foul them; this is likely to occur if the input socket is too near the corner of the box. Solder the three pieces of pcb screen (0·8in high) in place, soldering both sides of the board all along their length. Mount the feedthrough capacitors in the screens and lid. The one into the drain compartment should be about halfway up the screen, and the one into the gate line about 0·2in from the top of the screen. Cut out two small pieces of pcb about 0·125in square for use as mounting pads for the fet leads, and glue them down flat to the ground plane on each side of the gap in the screen. Mount the input and output sockets and C2, making sure that the sockets do not foul the sides of the box. If four-hole mounting sockets are used they can be pushed through the pcb from the inside of the box and soldered to the ground plane inside the box. Single-hole fixing sockets can either be used in this way or bolted in. SMA, TNC or BNC sockets are particularly suitable on grounds of size, but BNC are rather less reliable electrically as they can become intermittent after a lot of use. N type sockets are too large.

Adjust the distance by which the input socket protrudes above the pcb so that C1 can easily be soldered to both C2 and the input socket. Next, bend up the input inductor L1 from some copper sheet about 0·040in thick, and solder it in place—at the grounded end first and then the end resting on C2. All the other components can then be installed. Take care when soldering to the Johanson trimmers, as the top

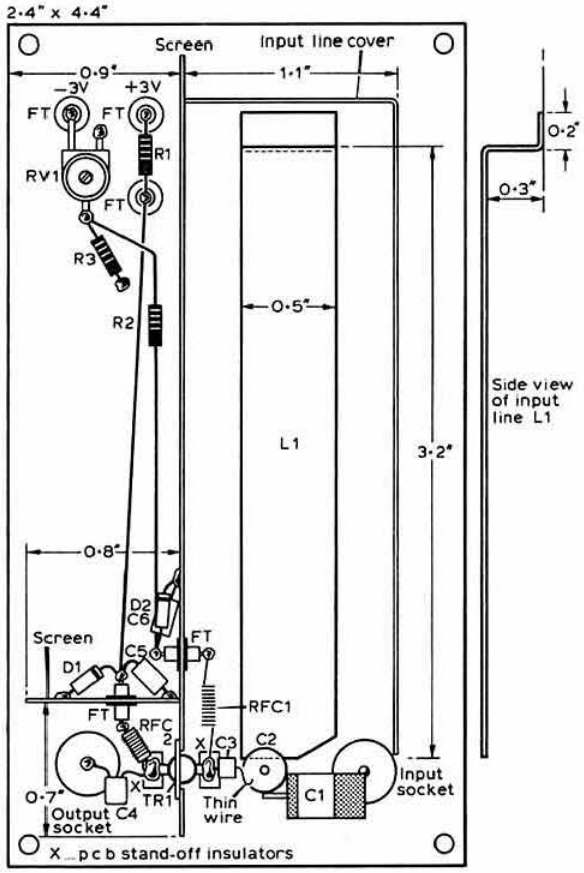
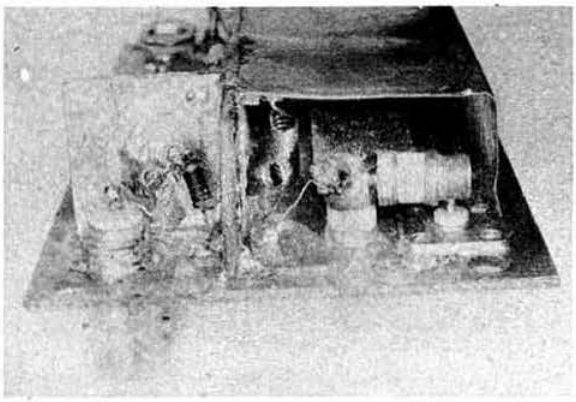


Fig 6. Layout of the gasfet preamplifier



The gasfet preamplifier before installing the final screen across the fet and input line

connections can become unsoldered from the body if they get too hot. A piece of flexible wire, rather than copper strip, should be used to connect C2 to C3 to prevent any stress being applied to C3. Next bend up the screen to cover the top, side and end of L1, and solder it in place all along the joins. It should stop just at the end of L1, leaving access to both the variable capacitors and the fet, and be about 0·3in above the copper line.

At this stage it is worth checking that the line can be made to resonate at 432MHz with C1 set approximately midway and with a 50Ω load on the input socket. Apply power and check that the correct voltages appear at the fet connection pads.

The next step is to install the gasfet. This requires sensible precautions when handling it, to avoid damage due to transient voltages, particularly as the devices are quite expensive. A few simple precautions are:

(1) Do not handle the device in a room where one can draw sparks from objects after walking across the floor.

(2) Touch earthed objects frequently.

(3) Touch the source first when picking up the gasfet.

(4) When installing the device in the amplifier, hold the amplifier at the same time, thus keeping them both at the same potential.

(5) When soldering the gasfet into the circuit, unplug the iron from the mains and ensure that the iron is earthed to the pcb during soldering.

For devices in the P103 package (threaded stud mounting), drill a 1·2mm diameter hole in the pcb between the two stand-off pads. The lead with a 45° cut across the end is the gate. Bolt the device in place, being careful not to tear off the thin foil leads by allowing the whole package to rotate while tightening the nut. Solder the leads to the stand-off pads. For the cross-type package, solder the two source leads to the screens on each side of the stand-off pads. The gap between the two screens can now be closed by soldering some thin metal foil across it, and another foil screen can be soldered over the end and top of the input circuit, leaving access to adjust C1.

C1 will need to be about 1–2pF and C2 about 3pF. These components must be very low-loss, and Johanson or JFD types are recommended. Miniature ptfe dielectric gold-plated trimmers similar to those supplied by Vero have also been used successfully for C1. C3 is ideally a 100pF chip capacitor, but ordinary disc ceramic types may be suitable. RFC1 must also be of low-loss construction; it is about 15 turns of 26swg enamelled wire, self-supporting, 0·125in diameter with the turns slightly pulled apart. RFC2 is 10 turns of similar wire wound on the body of a resistor of a few hundred ohms (R4). The feed-throughs must work effectively at uhf, and the resistor R3 is just used as a stand-off insulator to support the preset, RV1.

The BFR34A preamp, Fig 7, is built in a very similar manner in a smaller diecast box, but screens will probably not be needed, other than the one shown in the layout in Fig 8.

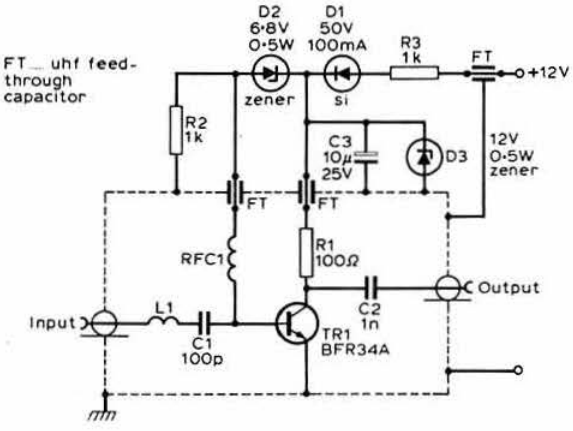


Fig 7. Circuit of the BFR34A preamplifier

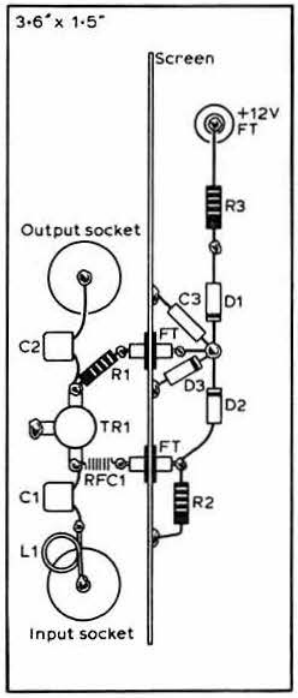


Fig 8. Layout of the BFR34A preamplifier

Power supplies

Gasfets are very sensitive to transients because of the very small capacitances and dimensions of the chip. The width of the gate is about 1 micron, so even relatively low voltages can produce very high electric fields in the chip. The manufacturer's maximum ratings are typically as follows:

Vgs	−6 to 0V.
Vds	0 to +6V.
Vdg	0 to 10V.
Pmax	500mW
Max forward gate current	2mA
Max reverse biassed gate leakage current	10μA

The gate is the electrode most liable to damage by transients, but once it is installed in the circuit it is fairly robust. By far the safest and very strongly recommended way of powering the preamp is from dry batteries. Holders for four HP7s can conveniently provide ±3V if a connection is made to the centre tap of the batteries. These should be mounted near the preamp, as excessively long leads will increase the chance of picking up transients from other circuitry, such as relays, which will also be at the masthead. It may be possible to design a transient-proof power supply, but perhaps rather risky to test it on one's own gasfet. The circuit given provides some protection, but zeners are fairly slow-acting devices and can still allow transients through. A very fast-acting zener diode is supplied by RS Components as a transient suppressor, with a rise time in the picosecond region and a very low dynamic resistance, and one of these may well be the solution to the problem. However, they are as yet untested by the authors, who regard batteries as the only really safe way of powering the preamplifier.

Testing

Set the bias preset to about half-way, then apply first the gate and then the drain supply. This order avoids the device taking Idss (50–100mA), which occurs if the gate bias is applied later. Reverse the order when switching off. The drain current should be set to 10mA initially, and can be monitored by measuring the voltage across the 47Ω resistor. The preamp may oscillate if it is run without a 50Ω load on the input.

Once the gasfet and a suitable second stage amplifier have been built, the matching of the gasfet will have to be carefully optimized to achieve the 0·5dB noise figure. The two preamps should be connected by a fairly short piece of cable to avoid introducing further losses; it should be the same piece of cable which will be used when they are installed in the system.

There are two approaches to the optimization. If facilities are available to measure and adjust the antenna accurately to 50Ω, then the preamps can be optimized on the bench when fed from a noise source with a 50Ω source impedance. The impedances should be kept to a vswr of less than 1·1:1 if the best noise figure is to be maintained. This method is the best, in that the preamp will be set up for 50Ω sources and can be measured on standard laboratory test gear.

Alternatively the preamps can be installed on the antenna, and noise injected by running the noise source into a small antenna near the main one, taking care that neither it, nor the presence of the operator, will upset the matching of the main antenna. Once it has been optimized in this way, the cables, relays etc between the antenna and the gasfet should not be changed, as they may alter the matching. With care, both methods can produce equally good results, since the actual antenna impedance is not important, provided that it is transformed to the correct impedance at the fet gate.

C1 should be set initially to 1–2pF, and C2 adjusted for best noise figure. Then C1 can be altered and C2 reoptimized. This procedure is necessary because both ends of C1 are floating, and the presence of the trimming tool alters the impedances. Both Vd and Id will affect the noise figure. The effect of Id is shown in Fig 3, while Vd has been found to produce a broad optimum in nf around 1·5 to 3V; typical values being 2·5V and 10mA. Whichever method is used, some form of noise figure indicating meter is necessary. A suitable instrument was described in [1] with some further modifications in [2]. This turns a noise source on and off at about 10Hz and, by measuring the ratio between the two noise levels at the audio output of

Components list

Gasfet preamplifier (Fig 5)

C1, 2,	0·8–10pF (MVM 010 or 106, or 0·4–6pF (MVM 006) Johanson or JFD trimmers
C3	100pF chip or disc ceramic
C4	1nF disc ceramic
C5, 6	10μF 6V tantalum
R1	47Ω 0·125W
R2	4·7kΩ 0·125W
R3	1MΩ 0·125W
R4	330Ω (see text)
RV1	22kΩ skeleton preset
L1	(see text)
RFC1	(see text)
RFC2	(see text)
FT	UHF type feedthrough capacitors
D1, 2	3·3V 1W zener diodes
TR1	GAT4, GAT5, ALF1000 or NE12683

BFR34A preamplifier (Fig 7)

R1	100Ω 0·125W
R2, 3	1kΩ 0·125W
C1	100pF disc ceramic
C2	1nF disc ceramic
C3	10μF electrolytic 25V
L1	1t loop 22swg 0·25in dia
RFC1	10t 26swg enam 0·125in dia
D1	50V 100mA silicon
D2	6·8V 0·5W zener
D3	12V 0·5W zener
TR1	BFR34A
FT	UHF feedthrough capacitor

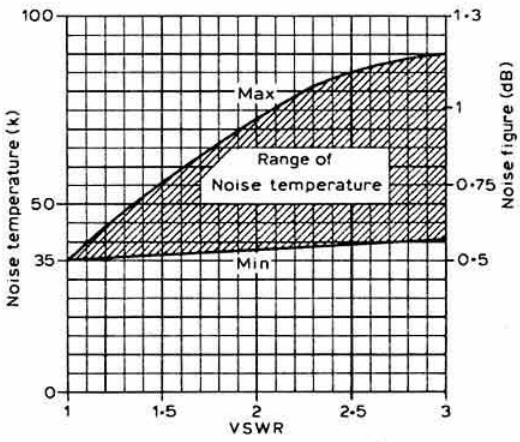


Fig 9. Variation of noise temperature of the gasfet preamp with source vswr

the receiver when the noise source is on and off, it can display the s:n ratio, which will be related to the noise figure. It is a very simple and extremely useful piece of test equipment, and can be used to optimize almost any receiver. In the absence of any test equipment it may be possible to set up the preamp by listening to a weak carrier, and adjusting for best s:n, but the nf meter is far more accurate, and quicker and easier to use. One word of warning: be careful not to tune up the gasfet preamp on the image frequency of the converter. These two preamps have enough gain to give quite a good noise figure even when tuned up on the image frequency, as some converters have very poor rejection of the image frequency; one using a 28MHz i.f. only had 10dB image rejection!

After optimization, the gain should be about 18dB and the overall noise figure 0·5dB. The BFR34A should give a noise figure of about 2dB (173K) and a gain of 13dB. The effect of the source impedance differing from 50Ω is shown in Fig 9. The worse the vswr, the greater the worst case noise figure, although—depending on the phase of the mismatch—it can also still be quite close to the best value.

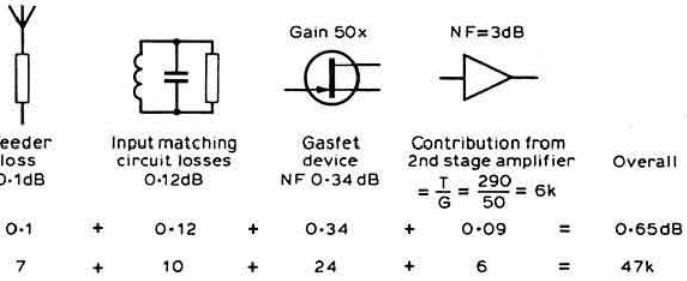

Gain 50x
NF=3dB
Feeder loss 0·1dB
Input matching circuit losses 0·12dB
Gasfet device NF 0·34 dB
Contribution from 2nd stage amplifier = T/G = 290/50 = 6k
Overall
NF added (dB) 0·1 + 0·12 + 0·34 + 0·09 = 0·65dB
Temperature added (k) 7 + 10 + 24 + 6 = 47k

Fig 10. Diagram showing the sources of noise in a typical receiving system

Measurement of the final noise figure is not easy. Few commercial nf meters are accurate to better than ±0·2dB in this region, and there are many other sources of error that can creep in. The best method is the hot/cold load technique, where the preamp is fed from 50Ω resistors held at two different temperatures. The ratio of the receiver noise outputs is measured, and compared with the ratio of the two temperatures and, hence, the ratio of the two noise powers. This technique is usually done using liquid nitrogen (77K) or dry ice for the lower temperature, and room temperature for the higher one. Kitchen table type measurements can be done using the temperature difference between ice and boiling water, but great care must be taken to ensure that the load impedance does not change between these two temperatures as this may also alter the noise output from the preamp. The liquid nitrogen/room temperature method was used to obtain the noise figures quoted here. They should be accurate to ±0·15dB.

Various gasfets have been tried in this circuit, including the Plessey GAT4, GAT5 and GAT6, the NEC NE12683, and the Alpha ALF1000, having gate widths from 1 to 0·5 micron; all of them giving very similar performance. The GAT2, having a 2 micron gate, is considerably worse at over 1dB. Although the first five devices all gave similar noise figures in the circuit, their inherent noise figures are actually somewhat lower than 0·5dB. The extra noise comes from the losses in the input circuit, and it is here that there is much scope for improvement.

Other devices which may be suitable but have not been tried by the authors are any of the other gasfets intended for use at 2–20GHz, having gate widths of 1 micron or less, such as the Mitsubishi MGF1400 series, or NEC V244 or V388. These devices are not cheap, in the region of £20–£100. However, these figures are not much more than a currently available commercial bipolar 1dB nf preamp, and their prices are still falling.

Installation

The preamp should be mounted as close to the antenna as possible, as any feeder loss will degrade the noise figure; 0·1dB loss will add 7K (0·1dB) to the system noise temperature. If the feeder from the masthead has a loss exceeding 1dB, then the second-stage preamp should be at the masthead as well. For best performance with these low noise figures, the antenna radiation pattern should also be considered. A high side-lobe level will result in high noise pickup from the surroundings but give maximum gain, whereas a low side-lobe level will give a quieter antenna with a lower gain. A compromise must therefore be reached if the antenna is to be used for both transmitting and receiving, as the requirements for the two conflict.

The noise coming out of the second stage can be split into contributions from several places in the preceding circuitry. The losses in a typical system are shown in Fig 10, giving an overall receiver noise figure of 0·65dB. Noise introduced by the antenna has to be added to this figure to get the overall system temperature, so it will be seen that a great deal of effort must be put into the rest of the system, as well as the first preamp, if it is to be used to its best advantage. The actual noise temperature of the fet chip is 15–30K (nf 0·2–0·4dB), depending on the device, so much of the noise is still coming from the passive components in the circuit, hence the strong emphasis on low loss in the design.

The two preamps may be considered to have a rather large gain (30dB) to put in front of the converter, as it will degrade the strong signal performance of the system. If this is an important consideration, then the whole receiver front-end must be designed with it in mind. It could be argued that for the applications for which it was intended, moonbounce or satellite reception, strong signals are the last thing to worry about!

References

[1] "An alignment aid for vhf receivers", J. R. Compton, G4COM. *Radio Communication* January 1976, p36.
[2] "Microwaves", *Radio Communication* October 1979, p934; March 1980, p270. □